PHOTOMETRIC PROPERTIES OF CANDIDATE PLANETARY SURFACE REGOLITH MATERIALS AT SMALL PHASE ANGLE: RELEVANCE TO SMALL BODIES IN THE OUTER SOLAR SYSTEM.

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Introduction: The reflection and the polarization change with phase angle of radiation scattered from particulate materials has been studied for a century in efforts to understand the nature of clouds, aerosols, planetary ring systems and planetary regolith materials. The increase in reflectance as phase angle decreases, the 'Opposition Effect' (OE), has been well documented in astronomical observations and laboratory studies. Variations in linear polarization near small phase angles have also been well studied in laboratory measurements[1]. While the phenomena have been intensely studied, a generally accepted physical explanation is still lacking despite many excellent theoretical modeling efforts.

Small bodies in the outer solar system are being given greater scrutiny in ground-based observations[2]. Spacecraft are also studying small bodies and ringed systems around the outer planets[3,4]. The Lunar regolith is being studied once again by sophisticated rover vehicles[5]. There is obvious need for more thorough laboratory reflectance and polarization measurements of candidate regolith analogues to provide a solid foundation for testing new theoretical advances[6] that address the many inconsistencies found when comparing laboratory investigations with theory. Our laboratory measurements provide empirical support for efforts to understand the data returned from observations of solar system objects by the next generation of deep space missions, earth orbiting telescopes and ground-based telescopes.

Method: Previously, our experiments have shown that the OE in particulate materials is due to two processes, Shadow Hiding (SHOE) and Coherent Backscattering (CBOE). SHOE arises because, as phase angle approaches zero, shadows cast by regolith grains upon one another become less visible to the observer (Fig. 1,left). CBOE results from constructive interference between rays traveling the same path in opposite directions (Fig. 1r). CBOE is premised on the returned radiation being multiply scattered[7,8].

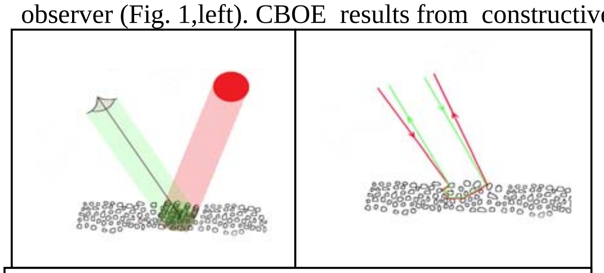


Fig 1. Conceptual illustration of the shadow hiding mechanism of the opposition effect, (left) and Coherent backscattering (right).

We have deconstructed the scattering process by fabricating a goniometric photopolarimeter (GPP). This permits us to present samples with monochromatic light that is linearly polarized in, and perpendicular to, the scattering plane. The GPP illuminates samples with both right handed and left handed circular polarization senses. Silicon Avalanche Photodiodes record the reflected radiation from the sample after it has passed through linear and circular analyzers[9]. This reductionist approach permits us to measure the reflectance and polarization phase curves and the change in linear and circular polarization ratio (LPR and CPR) with phase angle. LPR and CPR are found to be important indicators of the amount of multiple scattering in the medium. We can make measurements at phase angles between 0.056˚-15˚. This approach provides a way to distinguish between suggested models and to gain greater insight into the process of the scattering of electromagnetic radiation in a variety of media.

Experiment: A schematic drawing of the instrument is shown in Figure 2. The reflected signal from a 5 mW solid state laser of wavelength 635nm is simultaneously monitored in a stationary reference channel at fixed phase angle while it being recorded at variable phase angles by the detector on the movable arm. The instrument measures the reflected radiation in angular steps as small as 0.01˚. The sample is presented with

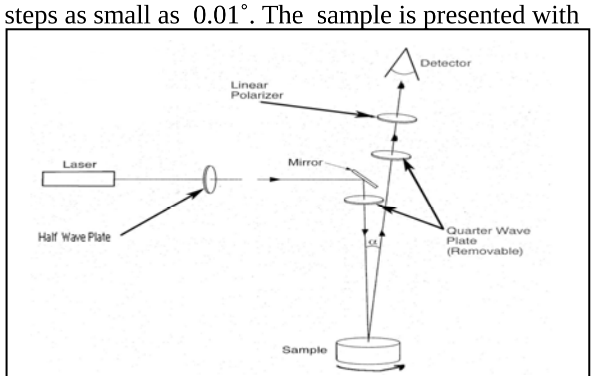


Fig. 2. A schematic drawing of the long arm goniometer that was used in this study.

linearly polarized light that is first parallel to and then perpendicular to the scattering plane. The reflected signal is analyzed using polarizing filters that are alternatingly oriented parallel and perpendicular to the scattering plane. This produces four phase curves. Then a quarter wave plate is inserted which renders the incident radiation left handed and right handed circular when the polarization of the incident radiation is changed by 90˚and the reflected radiation is analyzed after passing first through a quarter wave plate and then a linear polarizing filter. This produces four more phase curves. These, when combined, produce the integrated phase curve. The LPR and CPR phase curves are produced by ratioing the appropriate components.

The importance of this technique is that the amount of multiply scattered radiation can be determined by comparing the LPR and CPR as a function of phase angle. We define LPR and CPR in the same way as radar astronomers. LPR is defined as the ratio of the reflectance in the cross-polarized sense to that in the same-polarized sense as incident. CPR is defined as that returned in the same-polarized sense to that in the opposite-polarized sense as incident. Therefore, in a highly reflective medium where multiple scattering is important, LPR will decrease as phase angle decreases and CPR will increase as phase angle decreases. However in a highly absorbing medium where single scattering is important, both the LPR and CPR will decrease as phase angle decreases.

We made angular scattering measurements with a variety of well sorted particulate materials. Such materials are readily available as abrasives that are used in optical lens manufacturing. These are available in well sorted size fractions. Aluminum oxide (Al_2O_3) is parcularly useful because it is highly reflective (and therefore would be expected to exhibit much multiple scattering) and is available in particle sizes many times larger than the wavelength of the incident radiation and several times smaller. In this secondary engineering phase of the experiment we used different particle sizes of Al_2O_3 ranging from 0.1 to 30.09 microns.

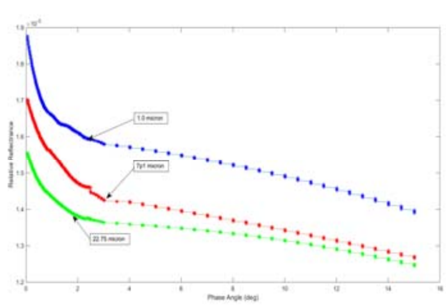
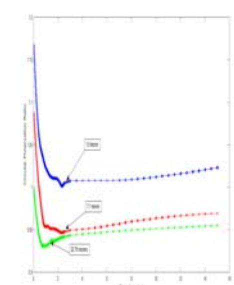


Fig. 3. Reflectance phase curves for three Al2O3 particle size fractions. The particle size that is closest to the wavelength of the incident light has the strongest opposition surge. The particle size, from top to bottom, is 1 micron, 7.1 micron, and 22.75 microns

The samples were gently poured into sample cups and the cups were lightly shaken to allow for settling. No attempt was made to pack the samples. Thus, the first surface encountered by the laser beam was the result of a natural settling process in order to best simulate a powdered surface of a planetary regolith. This resulted in the samples having approximately 75% void space as calculated from the mass of the powder in the cup compared to the volume of the cup. A typical set of reflectance phase curves for Al_2O_3 powders is shown in Fig. 3. The CPR and the angular location of the CPR minimum is shown in Fig. 4l and Fig 4r.



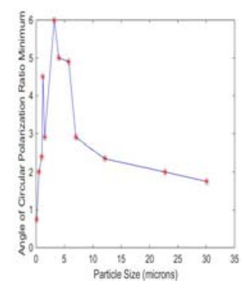


Fig 4l. CPR phase curve for the three samples shown in Fig 3. For all samples the CPR decreases with decreasing phase angle until a minimum is reached whereupon the CPR sharply increases. This is due to coherent backscattering at small phase angles in a higly multiply scattering medium.

Fig 4r. We find that the location of the minimum in the CPR phase curve is a function of particle size. For particle sizes much larger than the wavelength of the incident radiation, the location of the minimum is at small phase angle. For partice sizes that are close to the wavelength of the incident radiation, the CPR minimum is found to be at much larger phase angle. However, when the particle size is smaller than the wavelength of the indicent light, the CPR minimum becomes smaller.

Conclusion: The improved reconstructed GPP is able to measure the amount of multiple scattering in a particulate medium by comparing the linear and circular polarization ratio change with phase angle. At smaller phase angles in highly reflective material such as Al2O3, multiple scattering increases consistent with the coherent backscattering of photons that are multiply scattered in the medium. Future experiments will study these effects in particulate materials of different albedo and particle size.

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